

Charm Physics Prospects at Belle II

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(on behalf of the Belle II Collaboration)

The Belle II experiment is under construction at the KEK laboratory in Japan. Belle II will study e^+e^- collisions at or near the $\Upsilon(4S)$ resonance with the goal of collecting 50 ab^{-1} of data, which is a large increase over that recorded by the Belle and BaBar experiments. This data will provide a large sample of charm meson decays, and Belle II will have a very active charm physics program. Here we discuss some highlights of this program, focusing on measurements of mixing, CP violation, and leptonic decays.

*VIII International Workshop On Charm Physics
5-9 September, 2016
Bologna, Italy*

*Speaker.

1. Introduction

There are many strategies to search for new physics beyond the Standard Model. Besides studying B meson decays, for which the Belle, BaBar, and LHCb experiments were designed, one can study D meson decays, and all three experiments have produced numerous results in this area. While a hadron experiment such as LHCb produces a much larger sample of charmed mesons and baryons than does an e^+e^- experiment such as Belle, studying charm decays at an e^+e^- experiment has advantages. For example, an e^+e^- experiment has lower backgrounds, higher trigger efficiency, excellent γ and π^0 reconstruction (and thus η , η' , and ρ^+ reconstruction), high flavor-tagging efficiency with low dilution, and numerous control samples with which to study systematics. Due to good detector hermeticity and knowledge of the initial state energy and momentum, missing energy and “missing mass” analyses are straightforward. In addition, absolute branching fractions can be measured.

The Belle experiment at the KEK laboratory in Japan is now being upgraded to the Belle II experiment. The goal of Belle II is to collect a data set corresponding to 50 times what Belle obtained. Here we discuss the charm physics prospects of this large data set, focusing on measurements of charm mixing, CP violation, and leptonic decays.

2. Mixing and CP Violation

One emphasis of the Belle II charm physics program will be to make high precision measurements of charm mixing and search for CP violation. These measurements typically depend on measuring the decay time of D^0 mesons, and, due to an improved vertex detector, the decay time resolution of Belle II is expected to be superior to that of Belle and BaBar. Whereas Belle used a four-layer silicon-strip detector, Belle II will use four layers of silicon strips plus two layers of silicon pixels, with the smallest pixel size being $55 \times 50 \mu\text{m}^2$. These pixel layers will lie only 14 mm and 22 mm from the interaction point (IP).

Figure 1 (left) shows the resolution on track impact parameter with respect to the IP as a function of track momentum, as obtained from Monte Carlo (MC) simulation. Also shown are corresponding results from BaBar. The figure illustrates that the Belle II resolution should be half that of BaBar. Figure 1 (right) plots the residuals of decay time for a large sample of MC $D^0 \rightarrow \pi^+\pi^-$ decays. The RMS of this distribution is 140 fs, which is about half the decay time resolution of Babar (270 fs).

To study the sensitivity of Belle II to D^0 - \bar{D}^0 mixing parameters $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, and to CP -violating parameters $|q/p|$ and $\text{Arg}(q/p) = \phi$, two studies have been performed. The first study uses “toy MC” to generate $D^0 \rightarrow K^+\pi^-$ decays [1], and their decay time distribution is fitted. The second study uses a time-dependent Dalitz generator based on EVTGEN [2] to generate multi-body $D^0 \rightarrow K^+\pi^-\pi^0$ decays, and their time-dependent Dalitz distribution is fitted.

2.1 $D^0 \rightarrow K^+\pi^-$ Decays

For this study we generate an ensemble of 1000 “toy” MC experiments, with each experiment consisting of a sample of D^0 decays and a separate sample of \bar{D}^0 decays. The number of decays in each sample corresponds to 5 ab^{-1} , 20 ab^{-1} , and 50 ab^{-1} of data. For the full dataset

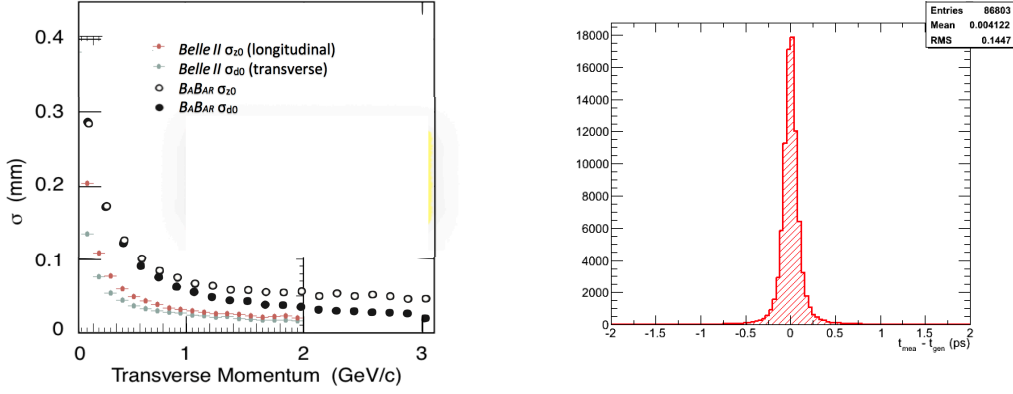


Figure 1: Left: Belle II track impact parameter with respect to the IP as a function of track momentum, as obtained from MC simulation. Right: Belle II residuals of decay vertex position, from MC simulation. The RMS of this distribution is 140 fs.

(50 ab^{-1}), there are 438600 $D^0 \rightarrow K^+ \pi^-$ decays. After generation, the decay times are smeared by the expected decay time resolution of 140 fs, and the resulting D^0 and \bar{D}^0 time distributions are simultaneously fitted. Backgrounds are not yet included in this study; however, a first look at backgrounds indicates that when backgrounds are included, the fitted errors increase by only a small amount.

The probability density functions used for the fit are the convolution of the following theoretical expressions with Gaussian resolution functions:

$$D^0(t) = e^{-\Gamma t} \left\{ R_D + \left| \frac{q}{p} \right| \sqrt{\bar{R}_D} (y' \cos \phi - x' \sin \phi) (\Gamma t) + \left| \frac{q}{p} \right|^2 \frac{x'^2 + y'^2}{4} (\Gamma t)^2 \right\} \quad (2.1)$$

$$\bar{D}^0(t) = e^{-\Gamma t} \left\{ \bar{R}_D + \left| \frac{p}{q} \right| \sqrt{\bar{R}_D} (y' \cos \phi + x' \sin \phi) (\Gamma t) + \left| \frac{p}{q} \right|^2 \frac{x'^2 + y'^2}{4} (\Gamma t)^2 \right\}, \quad (2.2)$$

where $x' = x \cos \delta + y \sin \delta$, $y' = -x \sin \delta + y \cos \delta$, and δ is the strong phase difference between $\bar{D}^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+$ amplitudes. The parameter R_D (\bar{R}_D) is the ratio of amplitudes squared $|\mathcal{A}(D^0 \rightarrow K^+ \pi^-)/\mathcal{A}(D^0 \rightarrow K^- \pi^+)|^2$ ($|\mathcal{A}(\bar{D}^0 \rightarrow K^- \pi^+)/\mathcal{A}(\bar{D}^0 \rightarrow K^+ \pi^-)|^2$). The preliminary results are listed in Table 1. The final Belle II sensitivity for $|q/p|$ is $< 0.1\%$, and that for ϕ is 6° . These results are a significant improvement over that which Belle and BaBar achieved.

Parameter	5 ab^{-1}	20 ab^{-1}	50 ab^{-1}
$\delta x'$ (%)	0.37	0.23	0.15
$\delta y'$ (%)	0.26	0.17	0.10
$\delta q/p $ (%)	0.20	0.09	0.05
$\delta \phi$ ($^\circ$)	16	9.2	5.7

Table 1: Preliminary results of a toy MC study of $D^0 \rightarrow K^+ \pi^-$ decays: uncertainty on mixing parameters x' and y' , and on CP -violating parameters $|q/p|$ and ϕ , for three values of integrated luminosity.

2.2 $D^0 \rightarrow K^+ \pi^- \pi^0$ Decays

For this study we generate an ensemble of 10 experiments using a time-dependent Dalitz generator based on EVTGEN [2]. Each experiment consists of 225000 $D^0 \rightarrow K^+ \pi^- \pi^0$ decays, corresponding to 50 ab^{-1} of data. The decay times are smeared by a resolution of 140 fs, and the decay model used to generate and fit the Dalitz plot is the isobar model used by BaBar [3]. Possible CP violation and backgrounds are neglected in this phase of the study. More details are given in Ref. [4].

The mixing parameters are $x'' = x \cos \delta_{K\pi\pi} + y \sin \delta_{K\pi\pi}$ and $y'' = -x \sin \delta_{K\pi\pi} + y \cos \delta_{K\pi\pi}$, where $\delta_{K\pi\pi}$ is the strong phase difference between $D^0 \rightarrow K^+ \pi^- \pi^0$ and $\bar{D}^0 \rightarrow K^+ \pi^- \pi^0$ amplitudes evaluated at $m_{\pi\pi} = M_\rho$. For this study the strong phase $\delta_{K\pi\pi}$ is fixed to 10° , and the fitted parameters are x and y directly. The results are shown in Fig. 2. The input values are $x = 0.0258$ and $y = 0.0039$, and the RMS of the distributions of residuals are $\delta x = 0.057\%$ and $\delta y = 0.049\%$. This precision is approximately one order of magnitude better than that achieved by BaBar [3]. The projections of a typical fit (one experiment in the ensemble) are shown in Fig. 3. In practice, to extract values for x and y requires knowledge of the strong phase $\delta_{K\pi\pi}$; this can in principle be measured at BESIII using CP -tagged $D_{CP} \rightarrow K^+ \pi^- \pi^0$ decays.

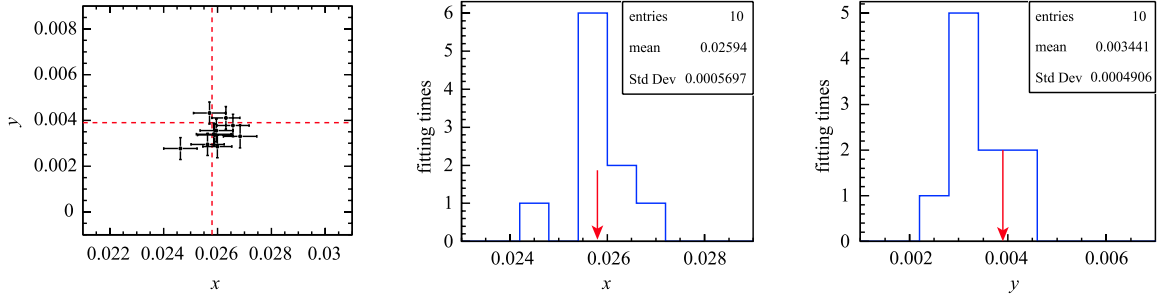


Figure 2: Left: preliminary results of fitting an ensemble of ten experiments, with each experiment corresponding to 50 ab^{-1} of data [4]. Middle and right: projections of the left-most plot. The RMS values of these distributions are $\delta x = 0.057\%$ and $\delta y = 0.049\%$.

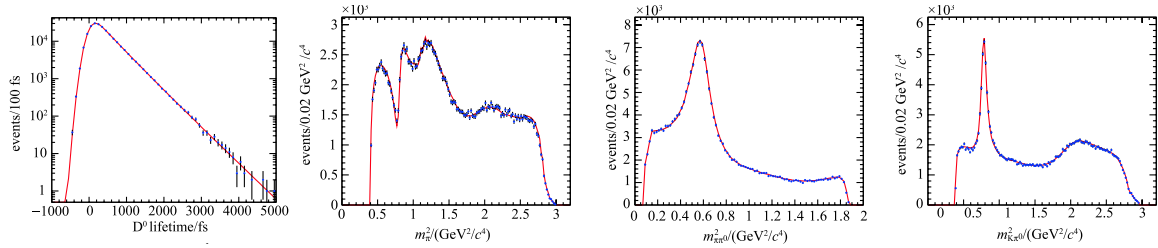


Figure 3: Projections of the fit to $D^0 \rightarrow K^+ \pi^- \pi^0$ events for one typical experiment in the ensemble [4].

2.3 Time-integrated (direct) CP Violation

Belle II will have excellent efficiency for reconstructing multi-body final states with very small detector-based asymmetries. Thus the experiment is ideal for searching for time-integrated (direct) CP violation in a variety of final states. A listing of D^0 , D^+ , and D_s^+ decay modes

that Belle has studied is given in Table 2. The table lists the CP asymmetry $A_{CP} = [\Gamma(D^0) - \Gamma(\bar{D}^0)]/[\Gamma(D^0) + \Gamma(\bar{D}^0)]$ measured by Belle, and the precision expected for Belle II. The latter is estimated by scaling the Belle statistical error (σ_{stat}) by the ratio of integrated luminosities, and by dividing the systematic error into those that scale with luminosity such as background shapes measured with control samples (σ_{syst}), and those that do not scale with luminosity such as decay time resolution due to detector misalignment (σ_{irred}). The overall error estimate is calculated as $\sigma_{\text{Belle II}} = \sqrt{(\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2) \cdot (\mathcal{L}_{\text{Belle}}/50 \text{ ab}^{-1}) + \sigma_{\text{irred}}^2}$. For most of the decay modes listed, the expected uncertainty on A_{CP} is $\lesssim 0.10\%$.

Mode	$\mathcal{L} \text{ (fb}^{-1}\text{)}$	$A_{CP} \text{ (%)}$	Belle II 50 ab^{-1}
$D^0 \rightarrow K^+ K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \rightarrow \pi^+ \pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \rightarrow \pi^0 \pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \rightarrow K_S^0 \pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.03
$D^0 \rightarrow K_S^0 \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \rightarrow K_S^0 \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \rightarrow \pi^+ \pi^- \pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \rightarrow K^+ \pi^- \pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \rightarrow \phi \pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \rightarrow \eta \pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \rightarrow \eta' \pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \rightarrow K_S^0 \pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03
$D^+ \rightarrow K_S^0 K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D_s^+ \rightarrow K_S^0 \pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \rightarrow K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

Table 2: Time-integrated (direct) CP asymmetries measured by Belle, and the precision expected for Belle II in 50 ab^{-1} of data.

3. Leptonic Decays

The low backgrounds of an e^+e^- experiment allow one to study purely leptonic $D_{(s)}^- \rightarrow \ell^- \bar{\nu}$ decays. The branching fractions of these decays are proportional to either $f_D^2 |V_{cd}|^2$ or $f_{D_s}^2 |V_{cs}|^2$, where f_D and f_{D_s} are decay constants, and V_{cd} and V_{cs} are Cabibbo-Kobayashi-Maskawa (CKM) matrix elements. Belle has measured the branching fraction for $D_s^- \rightarrow \ell^- \bar{\nu}$ [5], and inputting the value of f_{D_s} as calculated from lattice QCD [6] results in the world's most precise determination of $|V_{cs}|$. The $D_s^- \rightarrow \ell^- \bar{\nu}$ event sample for Belle II will be significantly larger than that for Belle, and this will allow for a more precise determination of $|V_{cs}|$. In addition, Belle II should measure $D^- \rightarrow \mu^- \bar{\nu}$ decays, and from this branching fraction determine $|V_{cd}|$ to $< 2\%$ uncertainty.

The method used by Belle to reconstruct $D_s^- \rightarrow \mu^- \bar{\nu}$ decays is as follows [5]. First, a “tag-side” D^0 , D^+ , or Λ_c^+ is reconstructed, nominally recoiling against the signal D_s^- . The decay modes

used for this are listed in Table 3. In addition, tag-side D^0 and D^+ mesons can be paired with a π^+ , π^0 , or γ candidate to make a tag-side $D^{*+} \rightarrow D^0 \pi^+$, $D^{*+} \rightarrow D^+ \pi^0$, $D^{*0} \rightarrow D^0 \pi^0$, or $D^{*0} \rightarrow D^0 \gamma$ candidate. The remaining pions, kaons, and protons in the event are subsequently grouped together into what is referred to as the “fragmentation system” X_{frag} . The particle combinations allowed for X_{frag} are also listed in Table 3. Because the signal decay is D_s^- , to conserve strangeness X_{frag} must include a K^+ or K_S^0 . If the tag side were a Λ_c^+ , then X_{frag} must include a \bar{p} to conserve baryon number. After X_{frag} is identified, the event is required to have a μ^- candidate nominally originating from $D_s^- \rightarrow \mu^- \bar{\nu}$, and a γ candidate nominally originating from $D_s^{*-} \rightarrow D_s^- \gamma$. The missing mass squared $M_{\text{miss}}^2 = (P_{CM} - P_{\text{tag}} - P_{X_{\text{frag}}} - P_\gamma)^2$ is calculated and required to be within a narrow window centered around $M_{D_s}^2$. The signal yield is obtained by fitting the “neutrino” missing mass distribution $M_V^2 = (P_{CM} - P_{\text{tag}} - P_{X_{\text{frag}}} - P_\gamma - P_{\mu^-})^2$, which should peak at zero. The missing mass distributions for Belle’s $D_s^- \rightarrow \mu^- \bar{\nu}$ measurement are shown in Fig. 4. The Belle signal yield, and the much larger yield expected for Belle II, are listed in Table 4.

The above method can also be used to search for $D^- \rightarrow \mu^- \bar{\nu}$ and $D^0 \rightarrow \nu \bar{\nu}$ decays [7]. In the latter case, the D^0 is required to originate from $D^{*+} \rightarrow D^0 \pi^+$, and the daughter π^+ momentum is used when calculating the missing mass. Requiring that M_{miss} lie within a narrow window centered around M_{D^0} results in an inclusive sample of D^0 decays. The Belle yield for this sample, and the expected Belle II yield, are also listed in Table 4. The Belle II yield would allow for a $7\times$ more sensitive search for $D^0 \rightarrow \nu \bar{\nu}$ (or any invisible final state) than that achieved by Belle.

Tag side:	D^0	D^+	Λ_c^+
Decay mode:	$K^- \pi^+$	$K^- \pi^+ \pi^+$	$p K^- \pi^+$
	$K^- \pi^+ \pi^0$	$K^- \pi^+ \pi^+ \pi^0$	$p K^- \pi^+ \pi^0$
	$K^- \pi^+ \pi^+ \pi^-$	$K_S^0 \pi^+$	$p K_S^0$
	$K^- \pi^+ \pi^+ \pi^- \pi^0$	$K_S^0 \pi^+ \pi^0$	$\Lambda \pi^+$
	$K_S^0 \pi^+ \pi^-$	$K_S^0 \pi^+ \pi^+ \pi^-$	$\Lambda \pi^+ \pi^0$
	$K_S^0 \pi^+ \pi^- \pi^0$	$K^+ K^- \pi^+$	$\Lambda \pi^+ \pi^+ \pi^-$
X_{frag} :	$K_S^0 \pi^+$	K_S^0	same as for D^+ tag + \bar{p}
	$K_S^0 \pi^+ \pi^0$	$K_S^0 \pi^0$	
	$K_S^0 \pi^+ \pi^+ \pi^-$	$K_S^0 \pi^+ \pi^-$	
	K^+	$K_S^0 \pi^+ \pi^- \pi^0$	
	$K^+ \pi^0$	$K^+ \pi^-$	
	$K^+ \pi^+ \pi^-$	$K^+ \pi^- \pi^0$	
	$K^+ \pi^+ \pi^- \pi^0$	$K^+ \pi^- \pi^+ \pi^-$	

Table 3: Belle $D_s^- \rightarrow \mu^- \bar{\nu}$ measurement method (see text) [5].

4. Acknowledgments

We are grateful to the organizers of CHARM 2016 for a well-organized workshop in a beautiful location, and for excellent hospitality.

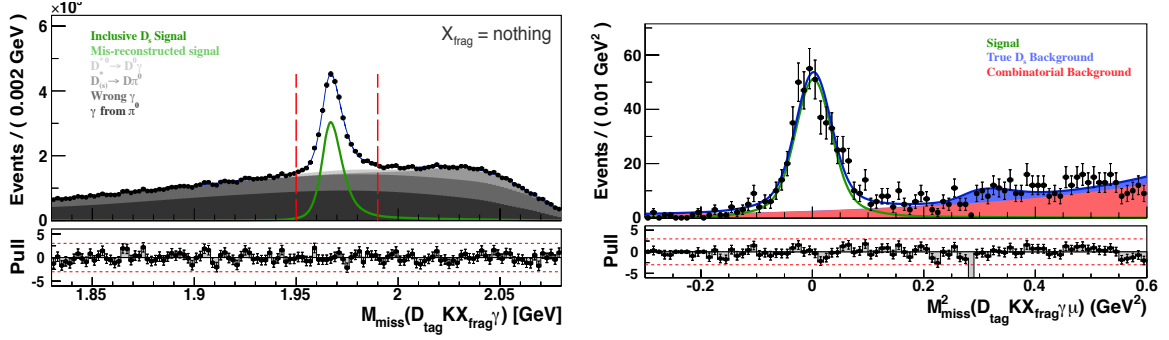


Figure 4: The Belle missing mass distributions used to measure $D_s^- \rightarrow \mu^- \bar{\nu}$ [5]. Left: $M_{\text{miss}} = \sqrt{(P_{CM} - P_{\text{tag}} - P_{X_{\text{frag}}} - P_{\gamma})^2}$, which should peak at M_{D_s} . Right: $M_{\nu} = \sqrt{(P_{CM} - P_{\text{tag}} - P_{X_{\text{frag}}} - P_{\gamma} - P_{\mu^-})^2}$, which should peak at $M_{\nu} = 0$.

Mode	Belle yield	Belle II yield (50 ab ⁻¹)
$D_s^- \rightarrow \mu^- \bar{\nu}$	492 ± 26 (913 fb ⁻¹)	27000
$D^- \rightarrow \mu^- \bar{\nu}$	—	1250
$D^0 \rightarrow \nu \bar{\nu}$	$(695 \pm 2) \times 10^3$ (924 fb ⁻¹)	38×10^6

Table 4: Belle’s $D_s^- \rightarrow \mu^- \bar{\nu}$ [5] and inclusive D^0 [7] signal yields, and the yields expected for Belle II. The latter are obtained by either scaling the Belle results or from MC simulation studies.

References

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